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CLAY MOBILITY

PORTUGUESE BEND, CALIFORNIA

PAUL F. KERR and ISABELLA M. DREW

Columbia University in the City of New York
Department of Geology
New York, New York 10027

Contract No. AF19(628)-5550

Project No. 8623

Task No. 862302

Scientific Report No. 1

April 1967

Contract Monitor: James T. Neal, Capt. USAF

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
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ABSTRACT

The south slope of the Palos Verdes Hills west of San Pedro, California, in the area known as Portuguese Bend contains an unusual landslide. Since the site is one of the choice residential areas of the southwest and 160 homes have been reported to have been removed as a result of the slide the locality has attracted wide interest.

The slide movement takes place in members of the Monterey Shale which contain bentonite; particularly the Portuguese Tuff. Samples of bentonite from the tuffaceous rocks are rich in Ca-montmorillonite which has definite thixotropic properties. When dry the clay is stable, but with the adsorption of water it swells and may ultimately flow. Overlying shale masses although substantial in themselves are slowly rafted down slope on the underlying bentonite-lubricated slip plane. Movements have frequently been measured in terms of a small fraction of an inch per day, but during a year cumulative movement in places may amount to 10 to 30 feet.

The physical properties of the clay have been studied in considerable detail and reveal a mobile material. Field observations indicate that enlargement of the slide area is also in constant progress. No field control of this situation has as yet been established. However, granted adequate drainage on the surface and along the slip plane below, plus impregnation by stabilizing additives it is suggested that a pattern of control might be developed. However, divided ownership inherent in the residential character of the terrain probably precludes the application of a control pattern to the slide as a whole. Further, the advance assurance of a successful research program in a trial area is an essential prerequisite to any attempted slide correction.

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Introduction

A large, slow moving landslide has long been recognized at Portuguese Bend. It occurs on the south slope of the Palos Verdes Hills, twenty-five miles south of central Los Angeles, California (Fig. 1). However, the slide became considerably more active following subdivision and building construction about 1956. By 1960 many homes had been damaged or removed and property damage was estimated in the millions of dollars. Now, 20 years after a U.S. Geological Survey map showing the slide was published, field observation still shows a steady but constant creep.

As the slide area appears, a wide variety of criteria of movement may be observed. Once attractive homes have gone through a process of slow demolition with gradual downhill movement until in many instances the wreckage has been removed. The topography has undergone gradual but substantial change. Palos Verdes Drive South, a 4-lane highway across the slide area, has been subject to constant repair, and widening on the up-hill side has been required repeatedly. At times offsets in the street pavement are clearly shown at east and west boundaries. The slide area between Palos Verdes Drive South and the seashore is pockmarked with slide scars, cut by fissures (Pl. 1), altered in elevations, and has shifted seaward (Fig. 2). The pleasure pier at the Portuguese Bend Club stands isolated from the shore, club buildings have disappeared, and the tennis courts have been tilted and fissured (Pl. 2, Fig. 2). Poles along power lines have moved. Trees have moved. Water mains now lie on the surface (Pl. 3, Fig. 1) with occasional special joints to provide adjustment for movement. Secondary roads have been fissured, changed in grade, and even ruptured in places. A concrete drainage ditch has been offset.

This investigation mainly concerns the clay involved in the under-lying earthflow. It has been undertaken in order to provide additional data on the causes of sliding and to examine fundamental characteristics

Plate 1

Aerial photographs of the same Portuguese Bend landslide area taken in 1956 and 1965. Note the absence of many houses between the highway and the shore in 1965. Dashed lines indicate approximate slide boundaries (1965).

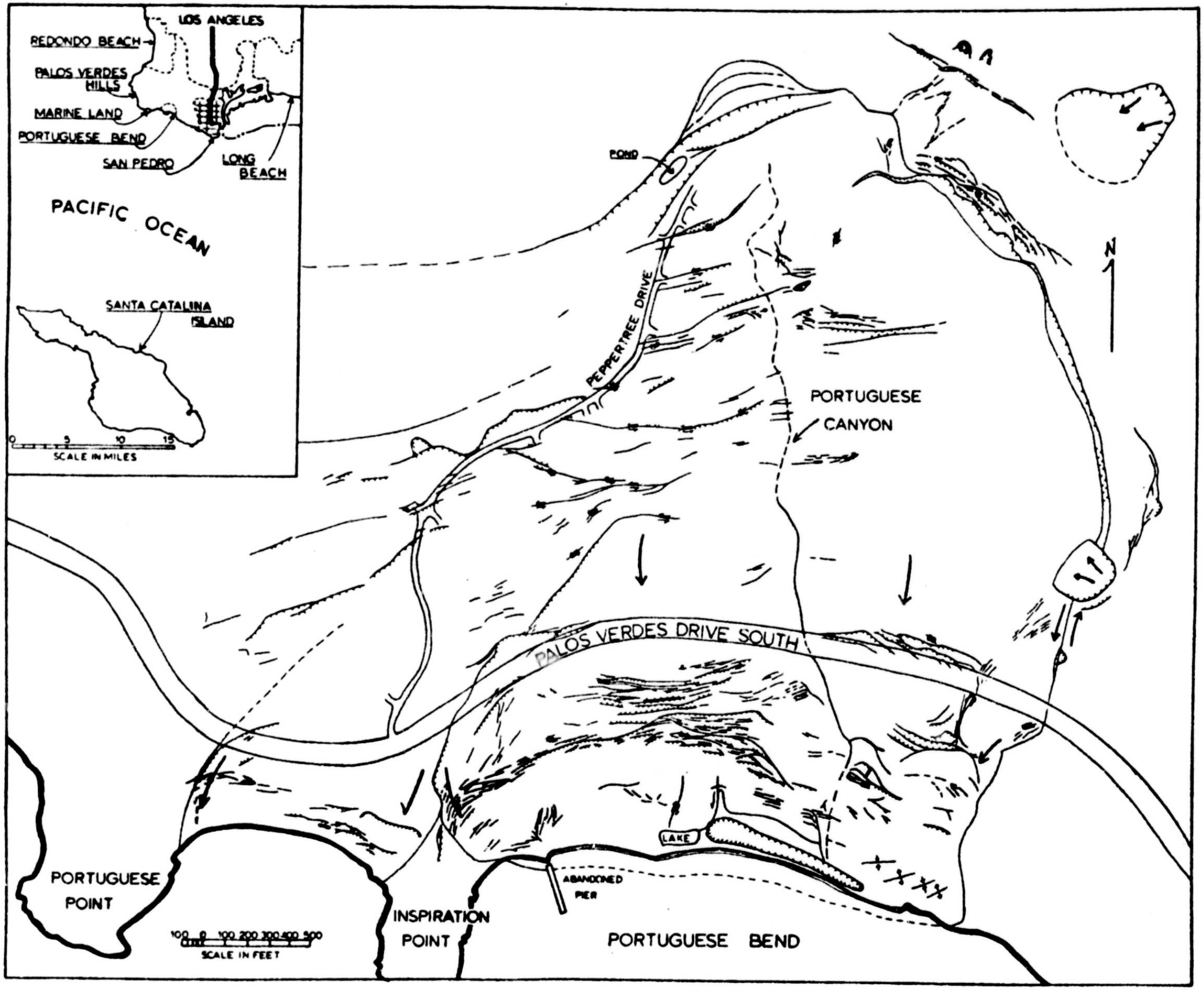

Fig. 1. The location of the main Portuguese Bend landslide area.

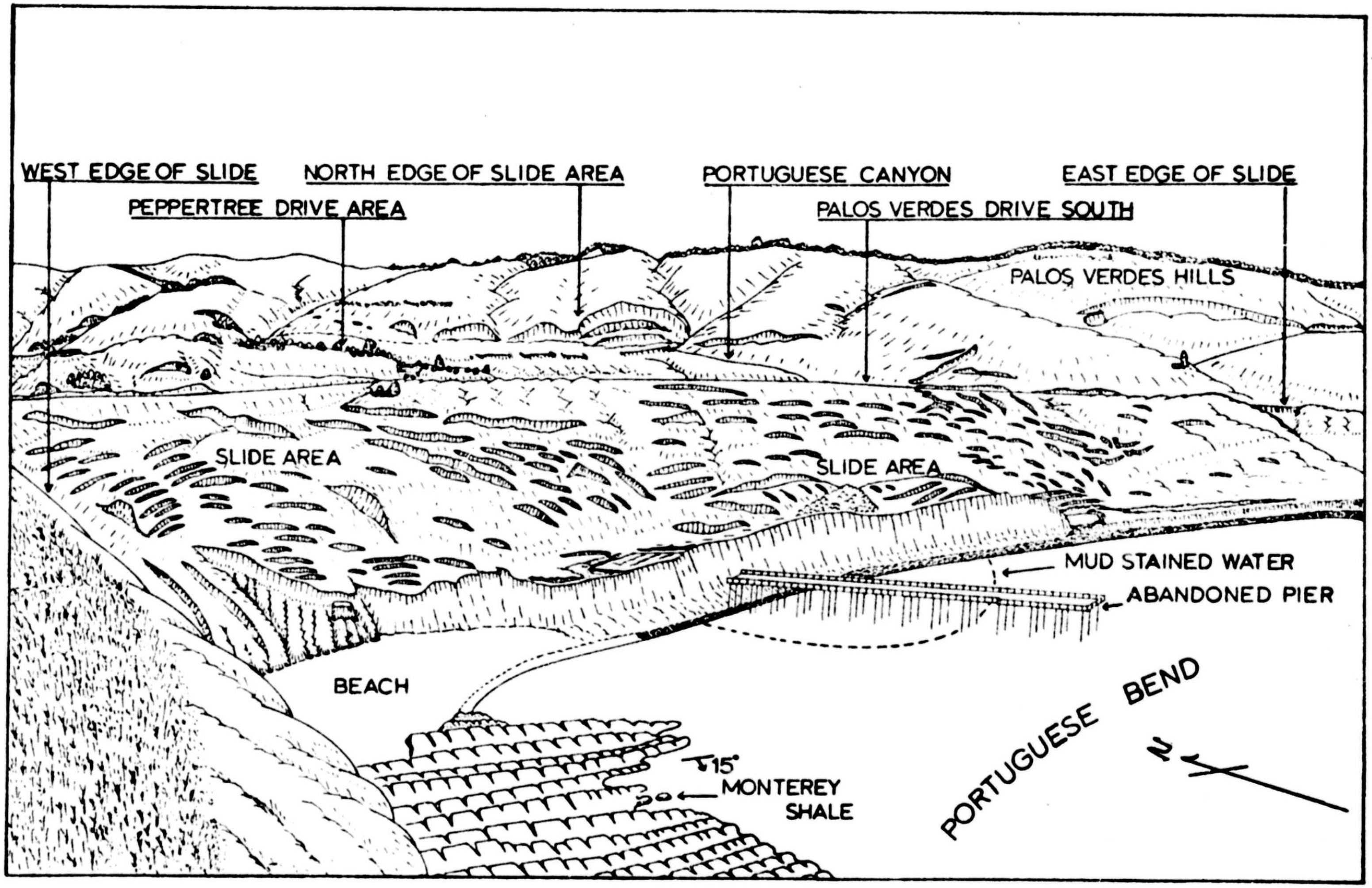

Fig. 2. A sketch of slide topography as observed in 1966.

with a possible bearing on slide control.

Acknowledgements

This study has been made possible through the support of the U.S. Air Force Cambridge Research Laboratories. The writers are indebted to Mr. Dennis A. Evans, formerly Head Engineering Geologist of Los Angeles County, to Dr. Perry L. Ehlig, California State College, Los Angeles, to Stone Geological Associates for field data and several of the samples investigated. We thank Miss Joan Settle who carried out many of the laboratory tests and aided in drafting figures.

Geological Features

An anticline, with a sinuous, but average N70° W strike follows the crest of the Palos Verdes Hills north of the Portuguese Bend landslide. The slide area extends up slope northward from the seashore about 4,000 feet and east-west about 6,000 feet. As shown by Woodring and others (1946, Pl. 1) on a geologic map and in accompanying text the slide occurs in the Altamira Member of the Monterey Shale (Miocene). They report that it occupies a more or less depressed structural basin on the south flank of the anticline. Massive siliceous shale and dolomitic strata along the shore strike N75° W and dip 15° S. At the sea cliff the dip is shown as north and Portuguese Tuff is exposed (Fig. 3). Up slope from the slide near the crest of the hills the strike is about N60°-70° W and the dip is 30-35° S. In the slide area between the upper and lower sequences of bed rock exposures slide deformation conceals the underlying strata.

The Monterey Shale where free from bentonite and even where intruded by basalt appears to form resistant masses not subject to slide action. This resistance is shown by Inspiration Point (Pl. 2, Fig. 1) and Portuguese Point (Fig. 1) which has long withstood extensive marine erosion.

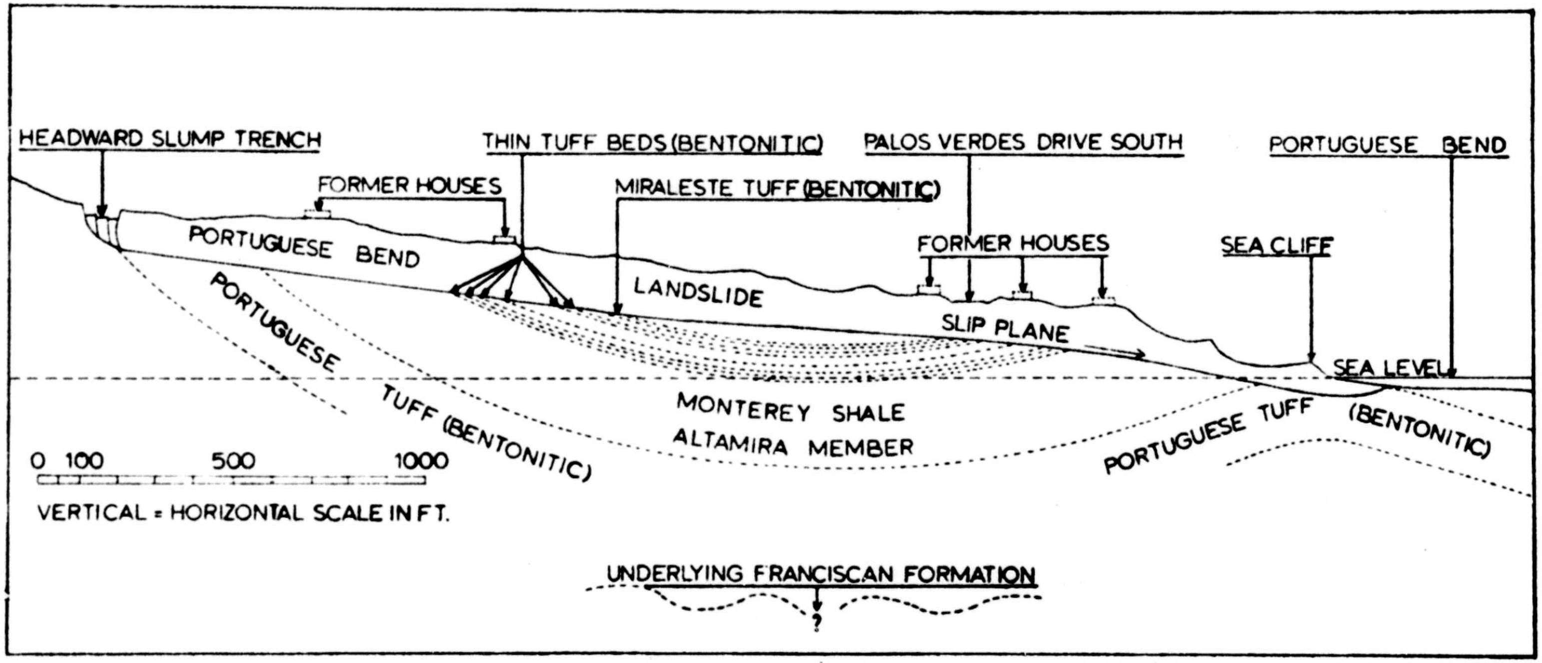

Fig. 3. An approximate structural interpretation of the Portuguese Bend landslide.

This ancient landslide was first recognized by hummocky topography combined with undrained arcuate depressions elongated at right angles to the direction of movement of the slide. As least one large depression and several smaller ones appear to have been produced by block tilting with rotational movement. Sediments in the lakes thus formed dip toward the head of the slide as pointed out by Merriam (1960). Some depressions have been formed by subsidence of slump trenches at the head of sliding units (Pl. 2, Fig. 4), while others may have resulted from elevation by uplift pressure in the lower part of the slide. More or less uninterrupted sedimentary strata in the shaly and tuffaceous material composing the slide indicate that in places blocks several hundred feet across must have moved almost intact (Pl. 3, Fig. 2). According to Merriam there is no rec rd of extensive movement in earlier historic times, although a country road crossing the ancient landslide area required frequent repairs.

Landslides at Portuguese Bend provide a complex of related lithologic, hydrologic, and structural features. The Altamira Shale Member of the Middle to Upper Miocene Monterey Shale in which most sliding occurs is at least 500 feet thick. Hard and essentially substantial cherty and silty shale strata make up the larger part of the section, but intercalated are several thin tuff beds which are in part bentonite. Above these is the Miraleste Tuff bed reported to be 19 feet thick. The Portuguese Tuff near the bottom of the Altamira Member is a light buff-colored tuff 150 feet thick that is partly bentonitic (Woodring, Bramlette and Kew, 1946, p. 21-22). Tuff debris probably derived from this bed is found at localities along the north, east and south margins of the landslide and in stream cuts within the slide area. The slide was long ago attributed to movment along a gliding plane formed by water-soaked

Plate 2. Stable and mobile areas at Portuguese Bend.

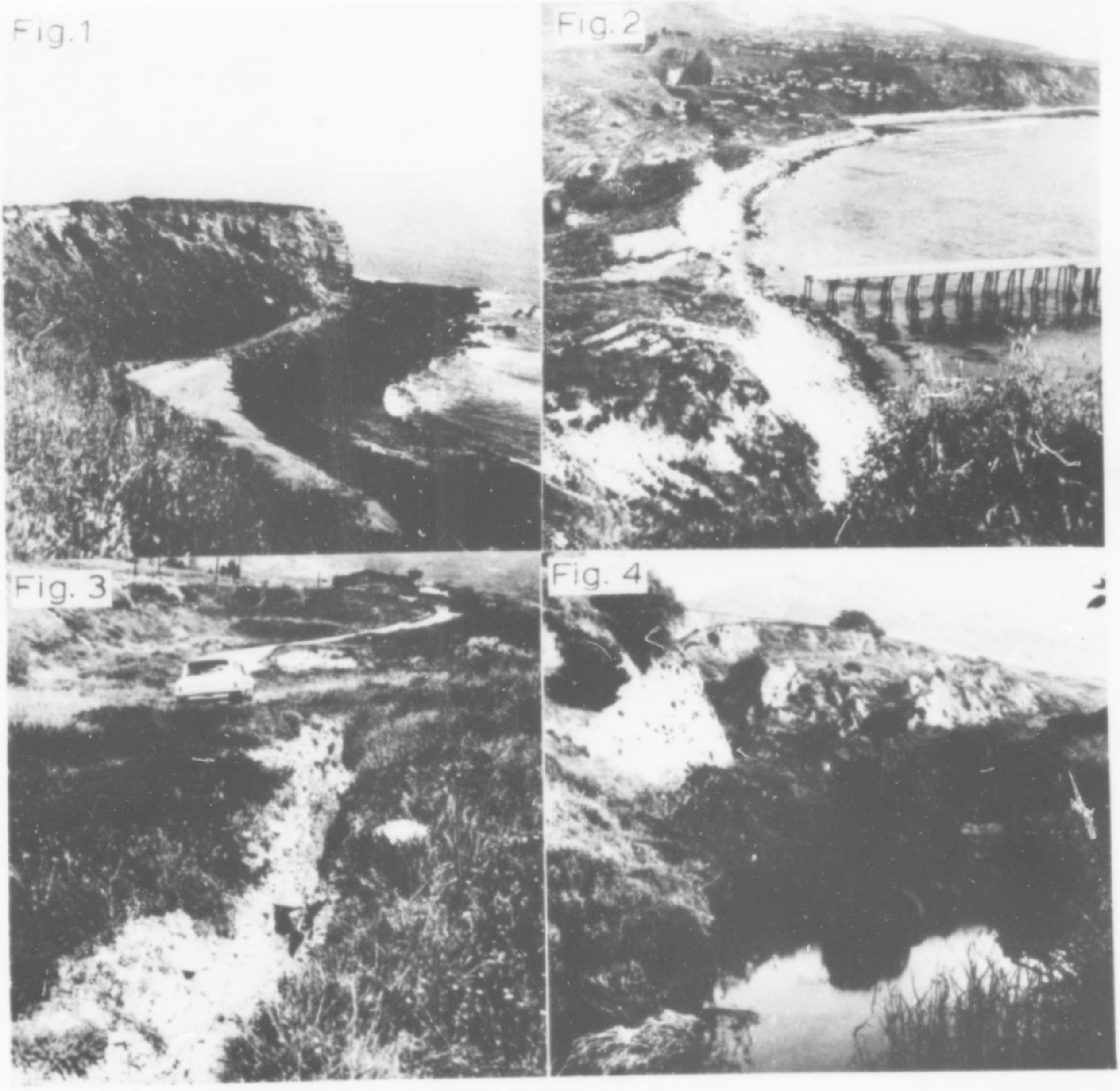

Fig. 1: The stable cliff of Inspiration Point, looking east. Resistant outcrops of Monterey Shale appear on the sea-cliff and along the seashore. Fig. 2: Slide area south of Inspiration Point. Tilted tennis courts and an abandoned pier appear in the foreground. Fig. 3: Fissure in slide area near Inspiration Point. The fissure is about 20 feet deep. Fig. 4: Pond between parallel fissures at head of Peppertree Lane (August, 1966). Water from fault lines would be expected to increase the mobility of bentonite along buried slip planes.

bentonitic tuff.

A cross section of the Portuguese Bend landslide is shown in Figure 3. It is based on stratigraphic data by Woodring and others (1946, p. 20-21), their geologic map (1946, Pl. 1), subsurface contours of the slip plane, by Stone Geological Associates, and geological observations on several occasions in connection with this study. The structure as projected beneath the slip plane is largely schematic, based on the interpretation by Woodring and others of a structural basin beneath the landslide.

The dip of the slip plane is south, aside from a concave depression beneath the sea-cliff where it extends below sea level and emerges off shore. Mud apparently extruded from the Portuguese Tuff on the ocean's floor stains the water near an abandoned pleasure pier (Pl. 2, Fig.2). No attempt has been made to distinguish the bentonitic from the nonbentonitic portions of the tuff. However, bentonite is restricted to tuff, although much less abundant than the replaced volcanic ejecta. Never-the-less, the accumulation of moist bentonite along the slip plane as indicated by borings is believed to be adequate to provide a lubricated surface for movement as suggested by physical tests.

Earth Movements

Beginning in 1956, approximately one-fourth of the previously known landslide area became noticeably active (Pl. 1). Earthflow at the rate of 0.03 to 0.1 feet per day down a mean slope of 6.5° has continued since that time (Fig. 3). The cumulative effect of such slide action may be highly damaging in a residential area, but it is not immediately devastating. Motion differs greatly from such a slide as the 1950 quick clay slide at Surte, Sweden that moved on a slope of about 1° at a rate

of about 143 feet per minute (Caldenius and Lundstrom, 1956), and rafted houses hundreds of feet in a few minutes.

In a slide area of such slow movement, long and irregularly active, initiation of slide action by earthquakes seems unlikely. Merriam (1960) has suggested that wave erosion of the cliffs in the lower end of the seaward plunging structural trough may have initiated the first slides. However, in such a slow moving slide, where conditions likely to cause slide action exist, movement may be spontaneous. The mineralogical nature and physical conditions of slide material probably constitute the most important factors.

Prior to 1956, several dry years had produced deep dessication cracks in the landslide area. Then nearly five inches of rain fell in less than a week, none of which was apparently discharged into the sea through Portuguese Canyon. In addition, it has been estimated that at least 32,000 gallons per day of moisture (plus organic peptizing agents) entered the active slide area through cesspools connected with homes, most of which had been in place five to six years when sliding commenced. The influence of these factors on bentonitic clay would appear more than adequate to initiate slide action.

Present movement south of Palos Verdes Drive (Pl. 3, Fig. 3) consists of slow earth movement in which crushed debris and bentonite undergo plastic flow. North of the drive, larger blocks may move fairly intact (Pl. 3, Fig. 2), but are shifted relative to one another and in places exhibit marginal fissures. At the head of the slide, block rotation may be observed (Pl. 2, Fig. 2). A cyclic variation in slide movement can be correlated to precipitation with a lag of several months between rainfall and slippage (Merriam, 1960).

Earth movements along the east side of the landslide exhibit a

pattern of considerable interest. A photograph of this area, looking west from the east border of the slide published in 1946 (Woodring, Bramletter and Kew, Pl. 5), shows Pleistocene marine terraces with moderate south slopes toward the Pacific. Recent observations, although only partly supported by elevation data, clearly show major changes in slide topography since 1946. The sea cliff area (Pl. 3, Fig. 2), has undergone substantial uplift and apparently some migration seaward. Palos Verdes Drive South is now at least 100 feet north of its position in 1956 (Pl. 3, Fig. 1). The terrace area north of Palos Verdes Drive South now slopes northward away from the Pacific (Pl. 3, Fig. 3). An undrained basin recently a nursery for carnations has been created which is depressed tens of feet below its former level.

The depressed nursery area clearly represents considerable subsidence and the cause of the sinking is of interest. In the absence of sink hole development, it seems likely that bentonitic extrusion along the slide slip plane 50-150 feet below the surface may account for the subsidence. Extrusion of plastic clay along the seashore (Fig. 3) below sea level if long continued might account for volume changes adequate to cause the depression.

Samples Examined

Samples of material from the Portuguese Bend slide area were examined as follows:

A Highly expansive yellowish-gray bentonite from a cut on the south side of Palos Verdes Drive South, about 100 feet east of the active slide boundary. (Kindly supplied by Dr. Ehlig.)

B Greenish bentonite from the slide plane (also supplied by Dr. Perry L. Ehlig) taken from a boring near the head of the slide, made in

the summer of 1959, after the boring was offset by slide movement.

1 Gray to tan brecciated bentonitic clay from a road cut along Palos Verdes Drive South about 75 feet east of the edge of the slide.

2 Mottled bentonite mass mixed with broken strata from the slide front collected from the base of the sea-cliff near the former Portuguese Bend Club Pier.

3 Gray to tan bentonite from a cut along Peppertree Drive at the northwest portion of the slide.

4 Lignitic shale collected near the slide area.

5 Diatomite from crest of the Palos Verdes Hills collected northwest of the slide area.

Mineral Content

Samples A, B, 1, 2, and 3 are all bentonitic. The clays are highly expansive; their dry strength is great, but they absorb water readily, expanding to approximately twice their dry bulk and finally, upon continued addition of water, form a sticky to soupy slurry. These five samples give sharply defined x-ray diffractometer patterns for montmorillonite (Fig. 4). The interlayer cations are chiefly calcium. Some quartz is found in the coarser fractions, but the bulk of the material is relatively well-crystallized montmorillonite.

Montmorillonite in bentonite clay has been recognized previously in Monterey Shale (Kerr, 1931). On the basis of chemical analysis and x-ray diffraction data it would be classed as calcium montmorillonite.

Thin sections were made from Sample 2. Embedded in the extremely fine-grained matrix of bentonite are rounded particles averaging 0.5 to 1.0 mm. in diameter which are composed of aggregates of clay flakes. In

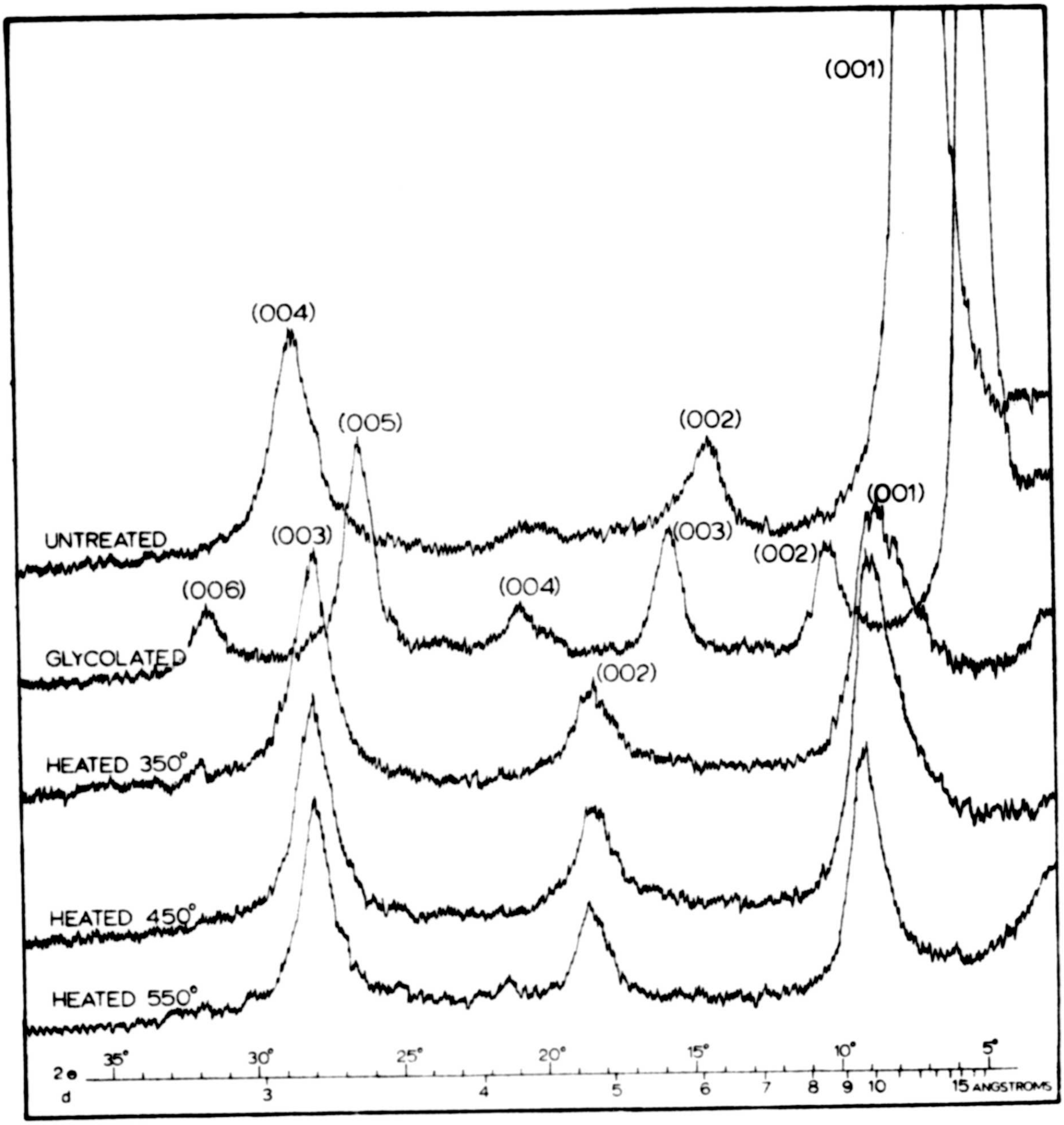

Fig. 4 X-ray diffractometer patterns of monotrillonite in 2 μ fraction of Sample 2. The (001) reflection expands 14 Å to 17 Å on glycolation. The structure collapses reversibly to 10 Å at temperatures as low 350°C but irreversible collapse is not encountered until 550°C, when the montmorillonite anhydride or illitic structure is formed.

studies elsewhere such particles have been interpreted as remnants of altered tuff (Schultz, 1963, p. C31). In the samples examined alteration has apparently destroyed all traces of shards.

Sample 4, a lignitic shale, with 4.36 per cent organic matter, is typical of the stable cherty and silty shales found in the slide area. Quartz and feldspar fragments form the bulk of this material. The mass disaggregates to some extent in water but does not swell or become plastic. X-ray diffractometer studies indicate that a small amount of illite-montmorillonite interlayered clay is present. Interlaying was not observed in the bentonite samples.

Sample 5, diatomite, shows typical diatom structures upon microscopic examination. The x-ray diffractometer patterns indicate that this bulky material has rather poor crystallity. The diatomite gives a negative test for carbonate and is not disaggregated by water containing a dispersing agent (5 per cent sodium metaphosphate).

Particle Size Measurements

ASTM Method D-22, the hydrometer method (1965) was used to determine the particle size range of the bentonites from Portuguese Bend. These clays are characterized by an unusually high colloidal content. They are gap-graded with some silt-sized particles present in all samples. Since only traces of quartz or other mineral fragments are present, as shown by x-ray diffractometer and microscopic investigation, these coarser particles are thought to be tuff particles. Water-saturated samples of the Palos Verdes bentonite are granular in appearance, with the grains apparently consisting of aggregates of partially altered volcanic material. Histograms (Fig. 5) illustrate particle size distribution. Samples 1, 2, 3, and B are from active slide areas and contain 60-70 per cent clay-sized

(minus -2µ) material. Sample A, from a road cut to the east of the active slide area, probabaly from the Portuguese Tuff Bed, contains considerably less fine clay (47 per cent). The particle size distribution curve shows this sample to vary from the others in being well-graded rather than gap-graded (Fig. 6).

Physical Properties of Clays

Samples collected during August, 1964, were found to have a natural moisture content of 62 per cent. Liquid limits for the bentonitic samples ranged between 90 and 110; plastic limits between 60 and 70. Thus even during the drier summer season the natural moisture of these clays lies within the range of plastic behavior.

Freshly sedimented bentonite was found to have a sedimentation bulk density of only 0.2g/ml. in distilled water. Thus it may be concluded that unconsolidated clay can hold four to five times its weight of water without becoming fluid. The clay is highly plastic, however, and the shear strength is low.

Viscosity and Flow Characteristics

One of the most remarkable features of the Palos Verdes bentonite is the ease and rapidity with which colloidal gels are formed. Gel formation led to considerable difficulty in determination of particle size ranges in certain of the samples by the ASTM Hydrometer Method. Only 50 grams of bentonite dispersed in 1,000 ml. of 0.5 per cent sodium metaphosphate solution were found to form a gel firm enough to support the weight (70 grams) of the ASTM soil hydrometer at any depth at which it was placed.

Quantitative measurements were made of the flow properties of the minus-2 µ fraction of the clay by means of the Brookfield Model RVT Viscometer. The yellowish-tan colloidal suspension investigated consisted

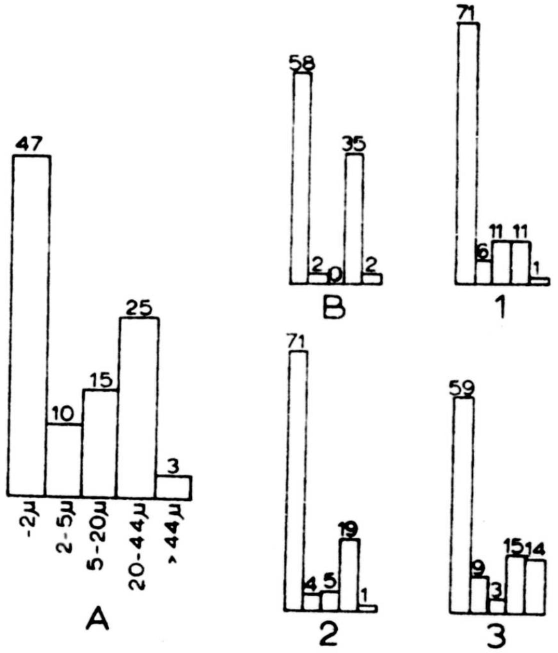

Fig. 5 Histograms showing particle-size distributions in Palos Verdes bentonites. Note that Sample A, from outside the slide area, contains the smallest amount of clay-sized material.

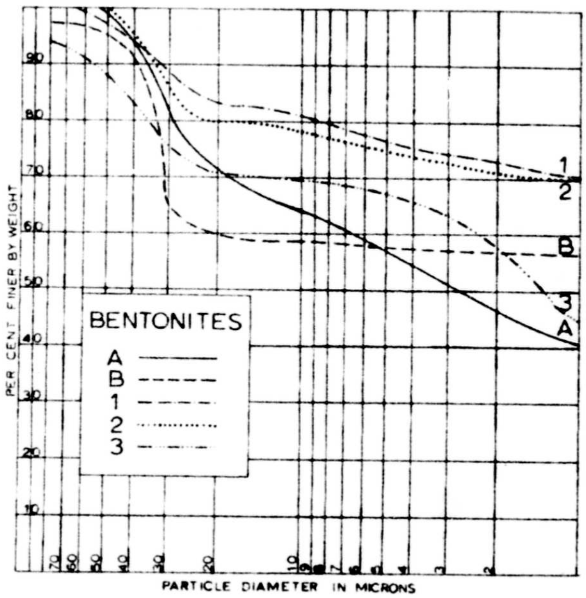

Fig. 6 Particle size distribution curves for the Palos Verdes bentonites. Most of these are gap-graded, consisting mostly of colloidal material and a few per cent coarser tuff particles.

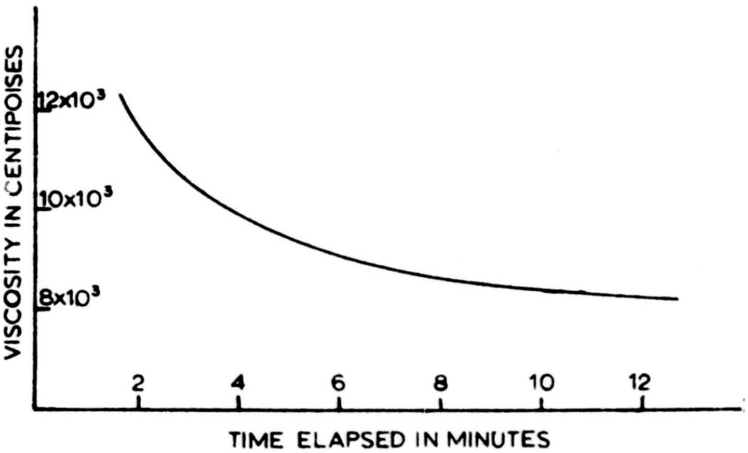

Fig. 7 Decrease in viscosity with time as the thixotropic gel breaks down.

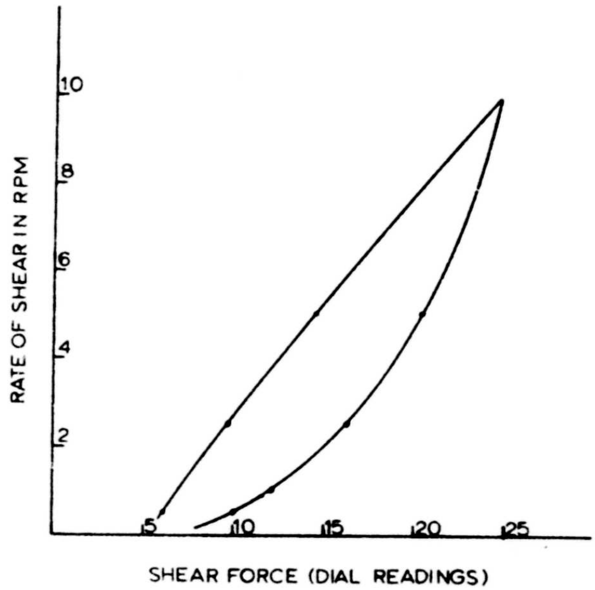

Fig. 8 Hysteresis Loop obtained for Palos Verdes clay.

Plate 3. Physiographic Features of the Portuguese Bend Landslide.

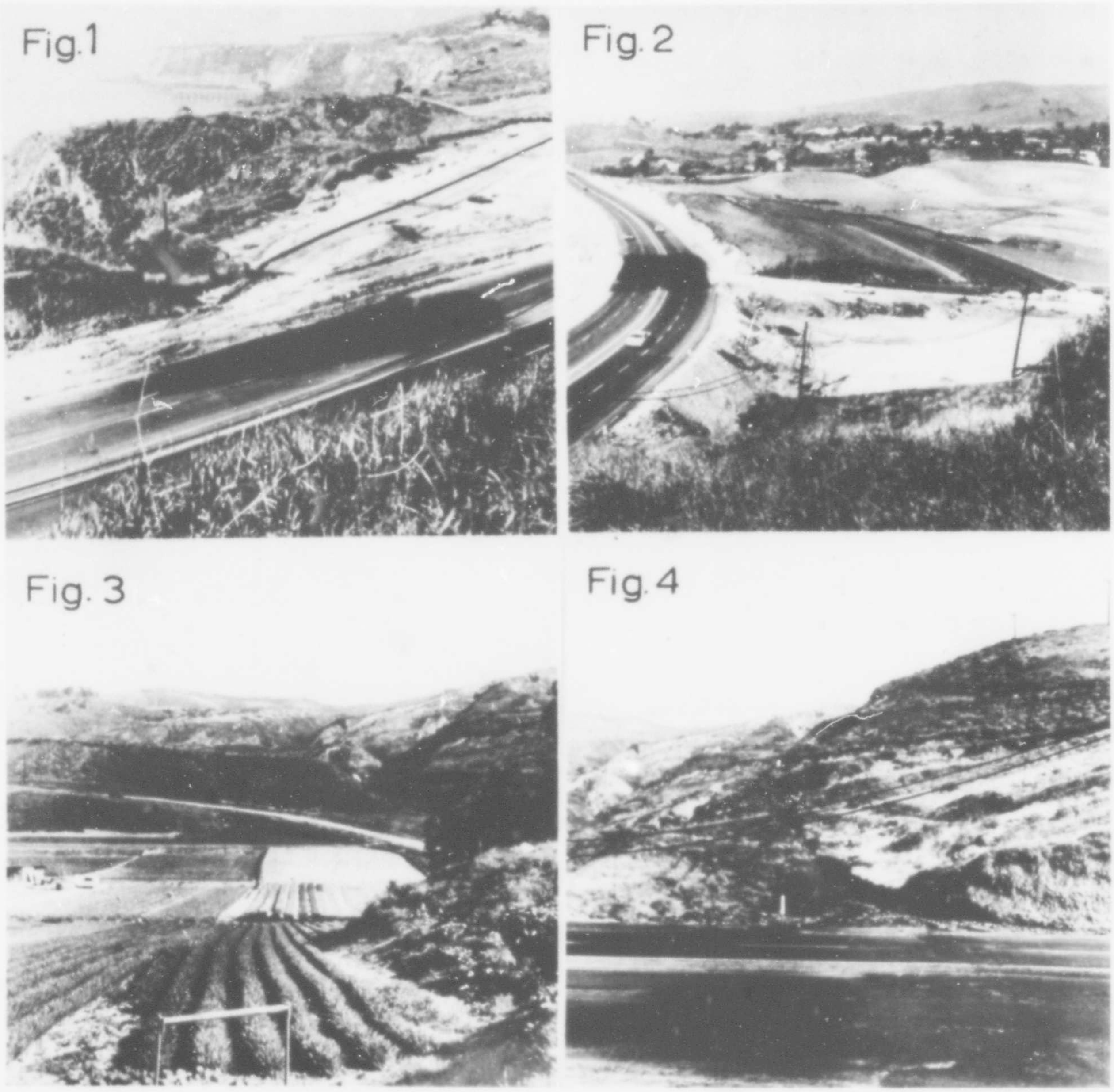

Fig. 1: Recently relocated (Feb. 1967) portion of Palos Verdes Drive South looking southwest at east margin of slide. Note service pipe on surface crossing former highway area. Fig. 2: Marine terrace tilted inland by slide rotation. Looking west along Palos Verdes Drive South at east margin of slide area. Fig. 3: Looking north across carnation nursery in area depressed by slide action. Fig. 4: Looking north at the scarp along the east margin of slide area north of Palos Verdes Drive South.

of 23 parts of water to 1 part of dry clay (moisture content=2300 per cent). The actual viscosity of the system, measured on the Brookfield Helipath Stand with Spindle T-A at 1 RPM, was found to be 128 poises. Clays from other locations, reported on elsewhere, showed no measurable viscosity at such high water contents.

The Palos Verdes bentonite is highly thixotropic. When the viscosity of the minus-2 μ clay fraction is plotted against the time elapsed, it is seen that the viscosity decreases as the system is subjected to constant shearing (Fig. 7). This is typical of thixotropic gels. The colloidal structure is almost completely destroyed in the bentonite after about 10 minutes at a rate of shear of 0.5 RPM.

When the rate of shear was increased from 0.5 to 10 RPM and then decreased again, a hysteresis loop (Fig. 8) was obtained, illustrating the fact that, in thioxotropic clays, the shear force, (and viscosity) at any given rate of shear is dependent on the amount of previous shear the system has undergone. Shearing causes breakdown of the particle links in the skeleton structure of the more or less flocculated clay-water system, thus reducing the viscosity of sheared clays.

When the thoroughly stirred clay-water system was allowed to stand for increasing periods of time, the original viscosity was regained, indicating that Brownian movement of particles permits the re-establishment of the sheared links in the colloidal structure. Thixotropic regain was found to be rapid for the first 15 minutes, during which time approximately half of the original viscosity was regained. Approximately 90 minutes is required for complete regain of the original viscosity.

The clay was found to be rheopectic, that is, the rate of stiffening increases when the beaker containing the suspension is tapped lightly. Rheopexy is a consequence of the increased particle collision frequency

in a gently agitated system. Mild agitation caused the original viscosity to be re-established in Palos Verdes clay in approximately 35 minutes, as compared with 90 minutes for the undisturbed system.

Influence of Water Content

Water content has a great effect on the properties of the Palos Verdes bentonite. As can be seen from Fig. 9, doubling the moisture content decreases the unconfined shear strength by more than 10 times. At the moisture content measured for the Palos Verdes clay, shear strengths would be on the order of only 1/4 ton per square foot.

An experiment was devised in order to study the influence of water content and overburden pressure on the stability of the clay strata at Portuguese Bend. A layer of bentonite 1/2-inch thick was spread between two rigid boards and the system adjusted to a constant slope of 1:10. The water content of the clay stratum was changed by the addition of increments of distilled water. The exact water content was measured after each test by oven drying and weighing samples of the clay. Loading of the upper board was also varied. Clay flowage was measured by timing the relative movement of vertical marks on the boards. The results of this experiment are illustrated in Fig. 10. At moisture contents greater than 120 per cent, the clay exhibited a slow plastic flow without loading. Loads selected would cover a range of about 0 to 150 feet, the estimated thickness of material above the slip plane at Portuguese Bend. As the load was increased, the water content at which the clay would show movement within a 24 hour period decreased. In this way, regions of stability and instability could be identified. Although an artificial model, this experiment is at least suggestive in considering movement of rock masses on moist clay under the field conditions at Portuguese Bend.

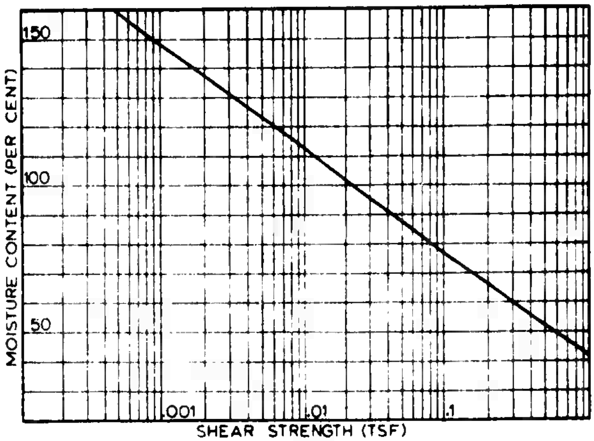

Fig. 9 Influence of water content on shear strength, as measured with Swedish Cone.

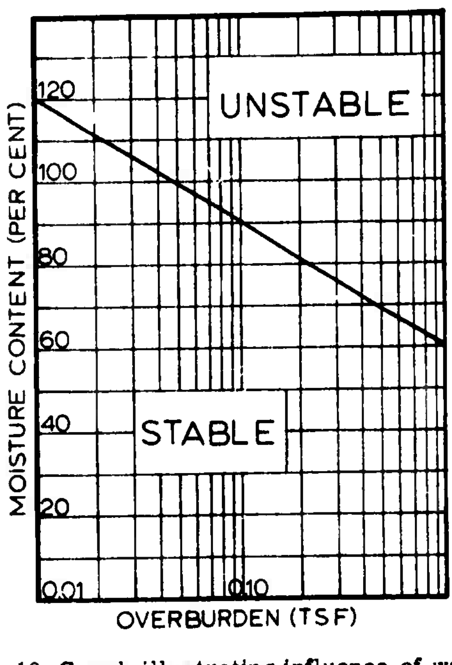

Fig 10 Graph illustrating influence of water content and overburden pressure on the stability of Palos Verdes bentonite. The greater the overburden pressure, the lower the water content necessary to produce movement.

Influence of Additives

Experiments were conducted in order to investigate the influence of lime on the physical properties of the Palos Verdes bentonite. Table 1 summarizes the results:

Table 1: Effect of Lime on Atterberg Limits and Shear Strength

	LL	PL	PI	Shear Strength
Clay in distilled water	110	71	39	0.02 tsf (at 113 per cent H_2O)
Clay in 2.5 per cent lime	123	102	21	0.07 tsf (at 114 per cent H_2O)

It is concluded that lime is effective in increasing the shear strength, since the addition of only 2.5 per cent lime more than triples the shear strength, even at high moisture contents. Lime also increases the liquid limit and the plastic limit but decreases the plasticity index, thus increasing the amount of water necessary to produce plastic flow in the clay.

Further experiments were carried out using Halliburton Company "Bengum". "Bengum" reacts rapidly with the clay and yields a cohesive granular product. The "Bengum" appears to form a coating for the Palos Verdes clay which may prevent further water absorption and swelling. The rapidity of the action between the "Bengum" slurry and the water already present, however, prevents penetration of the stabilizing agent into the clay mass. Therefore only the surface of the clay is affected.

Methods of Slide Control and Prevention

Several control methods have been tried and suggested at Palos Verdes. In 1957, the installation of 35 caissons 4 feet in diameter and 20 feet long and made of reinforced concrete failed to hold the sliding.

Some of the caissons failed through tilting, others were sheared and crushed, and material flowed around the remaining few in plastic flow. A program of fill and revetment at the toe reached the planning stage and some preliminary rock fill, but was apparently abandoned. Such a program might be effective in maintaining equilibrium by preventing erosion at the toe but probably would not be sufficient in itself to halt the slide.

Culverts and fill have been used in an attempt to prevent the entry of surface water into the clay strata. Unfortunately, slide movement has caused old filled cracks to reopen and new cracks to form.

The single most effective means of preventing sliding would appear to be the elimination of excessive water in the clay. At least it would appear feasible to drain water as accumulated in the slump trench at the head of Peppertree Drive (Pl. 1, Fig. 4). A program of drainage with upward sloping perforated pipe in the slide area, as effectively used, elsewhere in California, coupled with the diversion of water from the head of the slide would be helpful. This might be supplemented by the introduction of additives, such as lime, which should improve the properties of the clay. However any attempt at slide drainage and clay stabilization should be preceded by a program of field research in a selected experimental area.

Conclusions

Ca-Montmorillonite, in <2 μ particles, with highly adsorptive properties, a low shear strength when wet, and a notably thixotropic behavior is a recognizable constituent of tuffaceous members of Monterey Shale at Portuguese Bend. This material accumulated along one or more slip planes when wet provides a lubricating surface along which more substantial overlying siliceous shale moves gradually oceanward.

Mobile clay consisting essentially of montmorillonite is believed to be extruded from slip planes that emerge beneath the ocean. Removal of the clay from beneath portions of the slide area is believed responsible for subsidence east of Portuguese Canyon.

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13. ABSTRACT

The south slope of Palos Verdes Hills west of San Pedro, California, in the area known as Portuguese Bend contains an unusual landslide. The slide movement takes place in members of the Monterey Shale which contain bentonite; particularly the Portuguese Tuff. Samples of bentonite from the tuffaceous rocks are rich in Ca-montmorillonite which has definite thixotropic properties. When dry the clay is stable, but with the adsorption of water it swells and may ultimately flow. Overlying shale masses although substantial in themselves are slowly rafted down slope on the underlying bentonite-lubricated slip plane. Movements have frequently been measured in terms of a small fraction of an inch per day, but during a year cumulative movement in places may amount to 10 to 30 feet.

The physical properties of the clay have been studied in considerable detail and reveal a mobile material. Field observations indicate that enlargement of the slide area is also in constant progress. No field control of this situation has yet been established.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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